

# CROSS-SECTIONS FOR SQUARK AND GLUINO PRODUCTION AT HADRON COLLIDERS

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We present the cross-sections for the hadroproduction of squarks and gluinos in next-to-leading order of supersymmetric QCD. The four possible final states squark-antisquark, squark-squark, gluino-gluino and squark-gluino are analysed for the hadron colliders Tevatron and LHC. The dependence of the cross-sections on the renormalization and factorization scale is reduced significantly. The shape of the transverse-momentum and rapidity distributions remains nearly unchanged when the next-to-leading order SUSY-QCD contributions are included. The size of the corrections at the central scale, given by the average mass of the produced particles, varies between +5% and +90%.

## 1 Introduction

The colored squarks ( $\tilde{q}_L, \tilde{q}_R$ ) and gluinos ( $\tilde{g}$ ), the supersymmetric partners of the quarks ( $q$ ) and gluons ( $g$ ), can be searched for most efficiently at high-energy hadron colliders. As R-parity is conserved in the QCD sector of the Minimal Supersymmetric Standard Model (MSSM), these particles are always produced in pairs. At the moment they can be searched for at the Fermilab Tevatron, a  $p\bar{p}$  collider with a centre-of-mass energy of 1.8TeV [Ref.<sup>1,2</sup>]. In the future the CERN Large Hadron Collider (LHC), the  $pp$  collider with an envisaged centre-of-mass energy of 14TeV, will allow to cover mass values up to 1–2TeV [Ref.<sup>3</sup>].

So far most of the experimental analyses have been based on the lowest-order (LO) production cross-sections. For obtaining adequate theoretical predictions the LO cross-sections are in general not sufficient. The most important arguments in favor of an analysis that takes into account the next-to-leading-order (NLO) SUSY-QCD corrections are:

- The LO cross-sections have a strong dependence on the *a priori* unknown renormalization scale  $Q_R$  and the factorization scale  $Q_F$ . Consequently, the theoretical predictions have in general an uncertainty that is almost as large as the cross-section itself. By implementing the NLO corrections a substantial reduction of the scale dependence is expected.

- From experience with similar processes (e.g. hadroproduction of top quarks), the NLO QCD corrections are expected to be sizeable.
- An enhancement of the cross-section would lead to a higher value for the lower mass bounds for squarks and gluinos.
- In case of discovery of squarks and gluinos, a precise knowledge of the total cross-sections would be mandatory for the determination of the masses of the particles.

Here we report on the calculations of NLO SUSY-QCD corrections to the production of squarks and gluinos in  $p\bar{p}/pp$  collisions, based on the studies presented in Ref.<sup>4</sup>. For a more comprehensive report on this topic we refer to Ref.<sup>5</sup>.

## 2 Technical set-up

We consider the following hadronic production processes:

$$p\bar{p}/pp \rightarrow \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g} \quad (\tilde{q} \neq \tilde{t}), \quad (1)$$

where the chiralities and flavors of the squarks (e.g.  $\tilde{u}_L, \tilde{d}_R$ ) as well as the charge-conjugate final states (e.g.  $\tilde{q}\bar{\tilde{q}}$ ) are implicitly summed over. They are exemplified in Fig.1 for squark-gluino production.

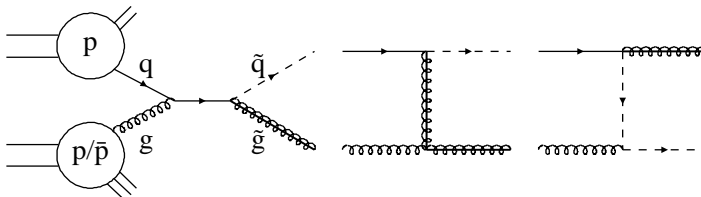


Figure 1: Generic Feynman diagrams for squark-gluino production in  $p\bar{p}/pp$  collisions.

In analogy to the experimental analysis, we exclude top-squarks from the final state and take all produced squarks to be mass degenerate. A study of the production of pairs of top-squarks is in progress, including the (model-dependent) mixing effects in the squark sector. At the partonic level

many subprocesses contribute at LO and NLO, corresponding to different flavors/chiralities of the squarks and different initial-state partons. The initial-state partons are made up of the massless gluons and the five light quark flavors ( $n_f = 5$ ), which are considered to be massless as well.

The NLO SUSY-QCD corrections include the virtual corrections (consisting of self-energy corrections, vertex corrections Fig.2(a), and box diagrams (b)), real-gluon radiation (c), and the radiation of a massless quark (d).

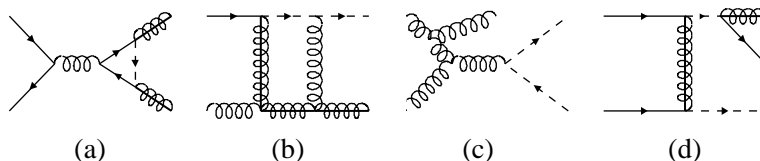


Figure 2: Generic virtual corrections [(a): vertex contributions, (b): box contributions] and real radiation [(c): gluon radiation, (d): quark radiation].

For the particles inside the loops we use the complete supersymmetric QCD spectrum, i.e., gluons, gluinos, all quarks, and all squarks. We have excluded the top-squarks from the final states. In order to have a consistent NLO calculation, however, we have to take the top-squarks into account inside loops. For the sake of simplicity we take them mass-degenerate with the other squarks. For the top quark we use  $m_t = 175$  GeV. Consequently the final results will depend on two free parameters: the squark mass  $m_{\tilde{q}}$  and the gluino mass  $m_{\tilde{g}}$ .

The divergences appearing in the NLO corrections are regularized by performing the calculations in  $n = 4 - 2\varepsilon$  dimensions. These divergences consist of ultraviolet (UV), infra-red (IR), and collinear divergences, and show up as poles of the form  $\varepsilon^{-i}$  ( $i = 1, 2$ ). For the treatment of the  $\gamma_5$  Dirac matrix, entering through the quark-squark-gluino Yukawa couplings, we use the ‘naive’ scheme. This involves a  $\gamma_5$  that anticommutes with the other gamma matrices. This is a legitimate scheme at the one-loop level for anomaly-free theories.

The UV divergences can be removed by renormalizing the coupling constants and the masses of the massive particles. In the case of the mass renormalization we have used the on-shell scheme and for the renormalization of the QCD coupling constant the modified Minimal Subtraction ( $\overline{MS}$ ) scheme. To preserve the supersymmetric relation between the gauge coupling (e.g. in the quark-quark-gluon vertex) and the Yukawa coupling (e.g. in the quark-squark-gluino vertex) we have to add a finite renormalization to the Yukawa coupling

[Ref.<sup>6</sup>]. The heavy particles (top, squarks and gluinos) are decoupled from the running of the strong coupling.

After carrying out this renormalization program, the cross-sections are UV finite. Nevertheless there are still divergences left over. The IR divergences cancel in the sum of virtual corrections and soft-gluon radiation. In order to separate soft from hard radiation a cut-off  $\Delta$  is introduced in the invariant mass corresponding to the radiated gluon and one of the produced massive particles. If soft and hard contributions are added up, any  $\Delta$  dependence disappears from the cross-sections for  $\Delta \rightarrow 0$ . The remaining collinear singularities, finally, can be absorbed into the renormalization of the parton densities, carried out in the  $\overline{MS}$  mass-factorization scheme.

If the gluinos are lighter than the squarks, gluinos can also be decay products of on-shell squarks,  $\tilde{q} \rightarrow \tilde{g}q$  [see e.g. Fig.2(d)]. However, these situations are already accounted for by the LO cross-section (e.g.  $\tilde{q}\tilde{q}$  production) and the subsequent decay. In order to avoid double counting, we restrict ourselves to irreducible final states in which gluinos do not evolve from on-shell squarks. For the wedge  $m_{\tilde{g}} > m_{\tilde{q}}$  we disregard, in the same sense as above, the decay of the gluinos to squarks.

### 3 Results

The hadronic cross-sections are obtained by the convolution of the parton densities with the corresponding partonic cross-sections. When discussing LO and NLO results, we calculate all quantities [ $\alpha_s(Q_R^2)$ , the parton densities, and the partonic cross-sections] in LO and NLO, respectively. We exemplify our results by gluino-pair production at the Tevatron and squark-gluino production at the LHC. The qualitative behavior of the other processes is quite similar.

As shown in Fig.3, we find that the theoretical predictions for the production cross-sections are nicely stabilized by taking into account the NLO SUSY-QCD corrections. In all processes, for both the Tevatron and the LHC, it is observed that the dependence on the renormalization/factorization scale  $Q$  ( $Q = Q_R = Q_F$ ) is quite steep and monotonic in LO, whereas the  $Q$  dependence is reduced significantly in NLO. Even a broad maximum develops at scales near one third of the average mass of the final-state particles. The variation of the cross-sections as a result of different NLO parametrizations of the parton densities is  $\leq 10\%$  at the Tevatron and  $\leq 13\%$  at the LHC, where the gluon densities are more important.

From now on we use GRV94 parton densities and conservatively take as default scale  $Q$  the average mass of the produced particles. The  $K$ -factors,  $K = \sigma_{NLO}/\sigma_{LO}$ , depend strongly on the process. This is exemplified in

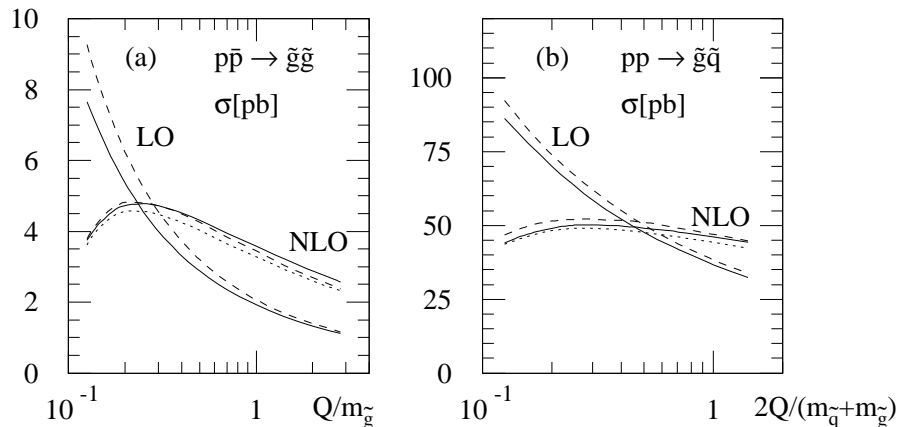


Figure 3: Scale dependence of the total hadronic cross-sections for (a): gluino-pair production at the Tevatron ( $m_{\tilde{q}} = 280\text{GeV}$ ,  $m_{\tilde{g}} = 200\text{GeV}$ ,  $\sqrt{S} = 1.8\text{TeV}$ ), and (b): squark-gluino production at the LHC ( $m_{\tilde{q}} = 600\text{GeV}$ ,  $m_{\tilde{g}} = 500\text{GeV}$ ,  $\sqrt{S} = 14\text{TeV}$ ). Parton densities: GRV94 (solid), CTEQ3 (dashed), and MRSA' (dotted).

Fig.4(a) for the Tevatron and in (b) for the LHC. For both collider types the NLO corrections are positive and large (up to +90%) for the dominant production cross-sections, involving at least one gluino in the final state. The corresponding  $K$ -factors also exhibit a sizeable dependence on the squark and gluino masses (especially the  $m_{\tilde{q}}$  dependence of  $K_{\tilde{g}\tilde{g}}$  is large). The NLO corrections for squark final states are moderate ( $\leq +30\%$ ). In case of discovery of squarks and gluinos, the inclusion of the NLO SUSY-QCD corrections is needed for an accurate determination of the cross-sections and the masses.

Apart from the total cross-sections, also distributions with respect to the rapidity ( $y$ ) and transverse momentum ( $p_t$ ) of one of the outgoing massive particles can be studied. The differential cross-sections are shown for gluino-pairs at the Tevatron in Fig.5 and for squark-gluino at the LHC in Fig.6. They are normalized to the total cross-section in the corresponding order. The  $K$ -factors for these distributions are independent of  $y$  for all practical purposes and hardly depend on  $p_t$ , where the NLO corrections render the distributions somewhat softer. Consequently, multiplication of the LO distributions with the above-defined  $K$ -factors for the total cross-sections approximates the full NLO results quite well.

Comparison of the NLO cross-sections with the cross-sections used in the

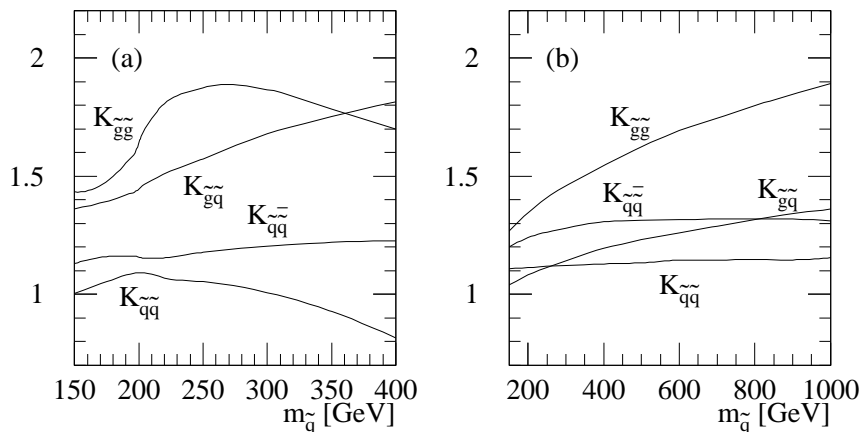


Figure 4:  $K$ -factors ( $K = \sigma_{NLO}/\sigma_{LO}$ ) for the four possible final states at (a): the Tevatron ( $m_{\tilde{g}} = 200\text{GeV}$ ), and (b): the LHC ( $m_{\tilde{q}}/m_{\tilde{g}} = 1.2$ ). Parton densities: GRV94.

experimental Tevatron analyses (LO, EHLQ parton densities, and a scale  $Q$  that equals the partonic centre-of-mass energy) reveals that the NLO corrections raise the lower mass bounds for squarks and gluinos by +10GeV to +30GeV. For the LHC the shift in the mass values between LO and NLO cross-sections amounts to +10GeV to +50GeV.

## Acknowledgments

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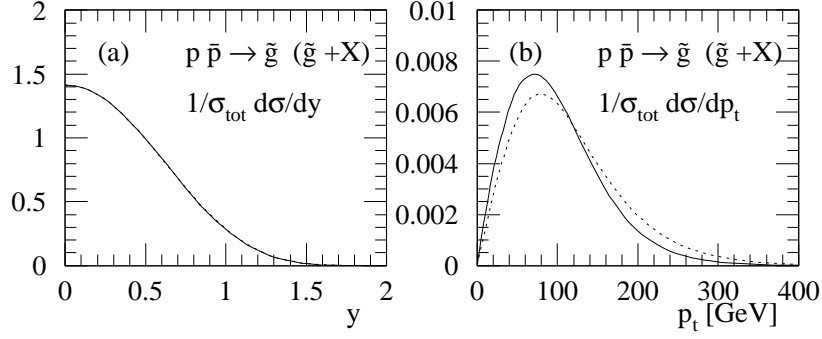


Figure 5: Normalized differential cross-sections for gluino-pair production at the Tevatron ( $m_{\tilde{q}} = 280\text{GeV}$ ,  $m_{\tilde{g}} = 200\text{GeV}$ ) with respect to (a): the rapidity of one gluino, and (b): the transverse momentum of one gluino. NLO (solid) and LO (dotted). Parton densities: GRV94.

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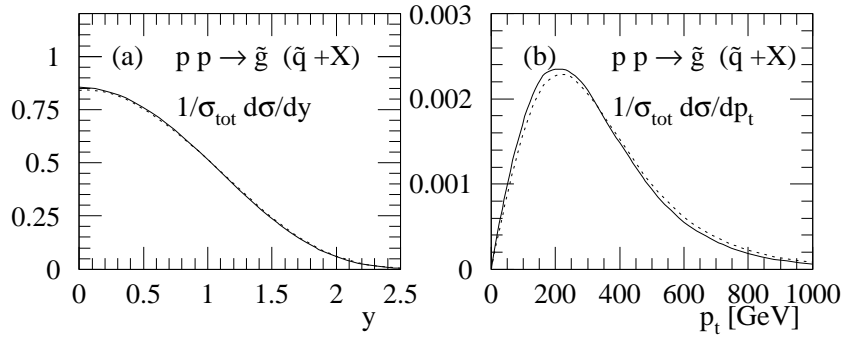


Figure 6: Normalized differential cross-sections for squark-gluino production at the LHC ( $m_{\tilde{q}} = 600\text{GeV}$ ,  $m_{\tilde{g}} = 500\text{GeV}$ ) with respect to (a): the rapidity of the gluino, and b): the transverse momentum of the gluino. NLO (solid) and LO (dotted). Parton densities: GRV94.